Advanced Respiratory Physiology

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Veterinary technicians effect, interpret and assess the respiratory system every day on almost every patient. To fully comprehend this amazing system one must review its basic and "advanced" physiology. This presentation will serve to outline the basic anatomy of the respiratory system and delve into more complicated aspects, such as pressures, blood flow and resistance, and finally briefly discuss the role of the respiratory system in metabolism and disease.

Basic anatomy

There are two major parts to the respiratory system: the conducting airways and the blood-gas interface. The conducting airways allow air to travel from the environment to the blood-gas interface to facilitate oxygenation and removal of carbon dioxide. The trachea is the initial tube connecting the mouth and larynx to the right and left mainstem bronchi. Following are the lobar and segmental bronchi. Finally, the last are the terminal bronchioles and respiratory bronchioles that contain alveoli. Within the alveoli is the blood-gas interface. Here, simple diffusion allows oxygen and carbon dioxide to flow across concentration gradients. The reason this works so well is Fick's law of diffusion. Fick's law states that gas movement is influenced by the area of the sheet and proportional to it, but inversely proportional to the thickness. Therefore, a large and thin sheet will transmit more gas than a short and thick sheet. Being that the blood-gas interface is around 50-100 meters long and about 1/3 mm thick, it is primed to move gas from capillary to alveoli and vice-versa, quickly.

The amount of air (volume) from the trachea to the terminal bronchioles is not involved in gas exchange and thus contributes to anatomic dead space. This is approximately 150mL in a human. Physiologic dead space is made up of areas of the lung that do not eliminate CO2. In normal patients anatomic and physiologic dead space are essentially equal, with adequate areas of alveoli available for gas exchange. However, in disease, physiologic dead space can increase from collapsed or alveoli filled with pus, blood or other fluid.

Blood flow to and from the lung is achieved from the right side of the heart, to the pulmonary artery, and into the lung via the pulmonary arteries. Blood then passes through a rich and dense network of capillaries, where it travels one cell at a time to millions of alveoli. Oxygenated blood then travels into the pulmonary veins and the pulmonary vein to the left atrium. The only thing separating a red blood cell from the alveoli lumen is the thin capillary and alveoli wall. The bronchial circulation is often forgetten. These vessels perfuse the lung parenchyma at the level of the bronchi and bronchioles.

Two important processes to note include the role of surfactant and the removal of foreign material from the lung. Due to the high pressures alveoli face and their liquid lining, one would think they would collapse much like popping packing material. However, they must stay open for gas exchange to occur. To help offset the surface tension across the alveoli wall they produce a thick (relatively) substance called surfactant. This help lower the surface tension by strengthening the wall of the alveoli. Additionally, the respiratory tract (essentially open to the environment) is constantly collecting dust and other foreign particles. The mucociliatory apparatus functions to move particles from the lower airways to the upper airways and out of the system. Dust that travels down to the bronchioles will be trapped in mucous and cilia will slowly raise the mucous up through the bronchi and into the trachea where it can be expelled. Foreign material in the alveoli gets trapped and cannot be effectively removed.

Lung pressures and volumes

Understanding respiratory physiology cannot occur without discussing properties of volume and pressure in the lung.

- Tidal volume: The amount of air taken in during a normal inhalation (and released during exhalation) (10-15 ml/kg)
- Vital capacity: The amount of air taken in and expelled during a maximal inhalation/exhalation.
- Residual volume: Amount of air left in the lungs after a maximal breath
- Functional residual capacity (FRC): Content of air left in lungs after a normal inhalation
- Total lung capacity: Total volume of lung- Vital capacity + residual volume
- Total ventilation: Respiratory rate x tidal volume
- Alveolar ventilation: (Tidal volume – anatomic dead space) x respiratory rate per minute

Pulmonary blood flow

In contrast to the systemic circulation, pulmonary blood "pressures" are quite low. If the average systemic mean arterial pressure is around 100 mmHg (Systolic of 120, Diastolic of 80mmHg) then the MAP of the pulmonary circuit is 15 mmHg with a systolic of 25 mmHg and a diastolic of 8 mmHg. This represents the ultimate function of the lung in regards to blood flow. Blood flow to the lung is never regulated like other organs and the blood must receive the entire cardiac output from the right side during every heart beat. To

facilitate ultimate diffusion by passing blood cells one by one through the capillaries, increases in pressure from the right heart could damage capillaries, and any constriction of the smooth muscle of the pulmonary vasculature would certainly cause the right side of the heart to work harder.

Transmural pressure: The pressure difference between the inside and outside of a capillary. If the pressure outside a capillary rises above the pressure inside the capillary will collapse. The capillary pressure is typically equal to atmospheric pressure. The alveolar pressure also is roughly equal to the atmospheric pressure. However if pressures inside the alveoli or surrounding the capillary increase the transmural pressure increases (greater pressure gradient) and the capillary collapses.

Intrapleural pressure: Pressure within the pleura surrounding and lining the thoracic cavity. Typically this pressure is negative, and becomes more negative on inspiration. However, pleural disease, such as a pneumothorax can increase it above atmospheric level.

Pulmonary circulation can deal with great changes in increased flow and resistance through some amazing attributes. Typically, systemic blood pressure will increase with changes in various cardiovascular parameters. If you run on a treadmill your blood pressure may increase from vasoconstriction or increased heart rate/stroke volume. However, if we increase the flow of blood to the respiratory system, the resistance often stays the same or lowers. This occurs from two different processes. The first process is termed recruitment. Recruitment refers to capillaries that previously did not conduct blood (not needed) to start doing so. If the pressure inside one capillary increases because of increased flow, and an additional capillary opens up to assist the overall resistance is lowered and kept the same. The second process is distension. And unlike vasodilation that is a widening of the arteries from the relaxation of smooth muscle, distension is a passive swelling of the capillaries from increased blood flow. These two processes function to maintain the resistance or pulmonary "blood pressure" under a wide variety of normal physiologic conditions.

Gas exchange

Does oxygen passively enter the lungs and diffuse into the pulmonary circulation? The answer is somewhat complex. The partial pressure of oxygen in room air and in our alveoli can be calculated. The partial pressure is equal to the inspired concentration (21%) multiplied by the difference between atmospheric pressure and the gas' water vapor pressure. In this case the PO2 is (0.21 x [760-47]) = about 150 mmHg. By the time that oxygen reaches our lungs the PO2 is around 100 mmHg. Oxygen is pulled from the alveoli at varying rates during demand. The rate of alveolar ventilation correlates to the delivery of oxygen to the capillaries. Thus, hypoventilation can cause hypoxia/hypoxemia.

Additional causes of hypoxemia include: diffusion impairment, shunt, and V-Q mismatch. Diffusion impairment is an uncommon cause of hypoxemia but can result from thickening of the blood-gas barrier. Shunt refers to deoxygenated blood that avoids oxygenation and travels from the right side of the heart to the left side. Shunt can be caused by several different mechanisms including: thromboembolism, recumbency (certain areas don't receive ventilation) or cardiac abnormalities like septal defects. Shunt results in hypoxemia as deoxygenated blood enters the arterial circulation. Shunt typically does not respond to 100% oxygen administration. The PO2 will rise but not to the projected value because the blood volume that is bypassing the lungs never becomes oxygenated. Additional dissolved oxygen may be detected when a blood gas is performed, but the hemoglobin may not respond to the additional oxygen. The last cause, V-Q mismatch, refers to ventilation and perfusion "mis-matching" across the lung. For ventilation and oxygenation to occur the alveoli must be open , air must flow into it, and blood must run across the alveolus. However, if one of these elements does not occur removal of CO2 and delivery of O2 may not occur. V-Q mismatching refers to examining the entire lung field and deciding whether there is a mismatch occurring- blood may not be flowing to certain areas, and certain alveoli may have blood flow, but no ventilation. If a ventilation obstruction occurs (airway blockage) the oxygen levels will fall but if there is blood flow, CO2 may elevate slightly but may not immediately increase. This is evident in the severe hypoxemia and cyanosis see in upper airway obstructions. Now on the other hand, if a blocked capillary does not deliver blood flow to the alveolus, the oxygen in the alveolus will increase as more is delivered to it, and the CO2 will eventually fall to 0 because inspired air contains no CO2. This represents a V-Q relationship of 0 (airway obstruction, no ventilation means V = 0) and one of infinity (perfusion = 0, Q = 0). This relationship between alveolar and arterial oxygen can be measured in the A-a or Alveolar-arterial gradient calculation.

A-a gradient:

A-a gradient = $P_AO_2 - P_aO_2$

$P_AO_2 = P_IO_2 - P_ACO_2/R$

SO: A-a gradient =[$P_IO_2 - P_ACO_2/R$] – PaO2

[R = respiratory quotient. Normally 0.8]

Note: this is at sea-level and cannot be used in >21% oxygen

Assume that PIO2 = 150 mmHg (oxygen partial pressure at 21%

Assume that alveolar (A) CO_2 = arterial (a) CO_2

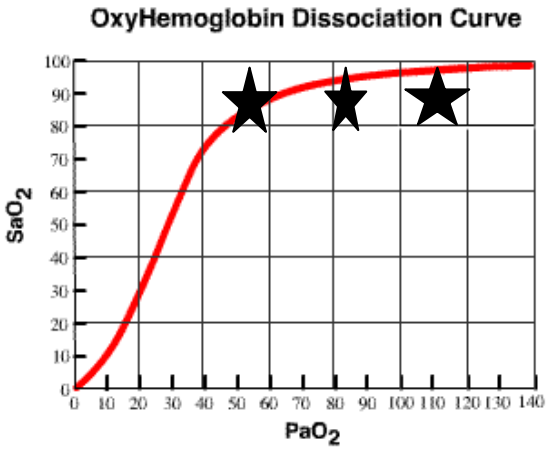
A-a gradient = [150 – P_ACO_2 / R]-P_aO_2

Example

An arterial sample is drawn that reveals a P_aO_2 of 72 mmHg on room air. The blood gas also reveals a CO_2 of 40 mmHg. We know that a PaO2 of 72 mmHg on room air is too low.

The A-a gradient is: (150 – 40/0.8) – 72 = 28. This is a high number. Meaning a gradient exists between the oxygen in the alveoli and the arterial oxygenation indicating a V-Q mismatch situation. Normal is less than 10. The gradient, under ideal conditions should be equal.

Relationship of dissolved oxygen to hemoglobin saturation

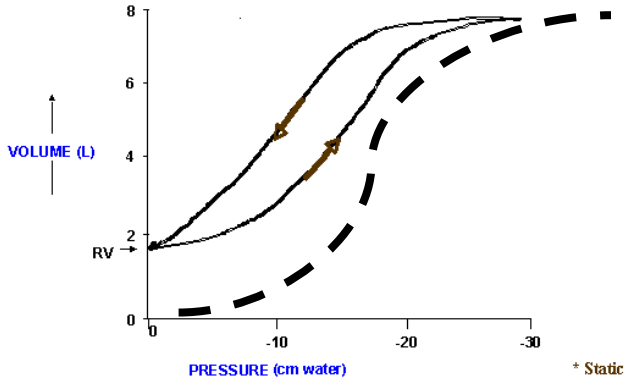


The PaO2 represents the dissolved oxygen gas in the bloodstream. However, metabolic delivery of oxygen depends on its rate of saturation with hemoglobin which is pumped around the body by means of the cardiovascular system. The key points here are that this is not a linear curve. If one looks at the ideal PaO2 level at room air (approximately 100mmHg) this corresponds to an SaO2 of about 94%. The PaO2 can continue up to 500 mmHg (ideal for breathing 100% O2) but the SaO2 only continues from 94-100%. A patient with a pulse ox (SpO2 = SaO2) of 98% or less under anesthesia breathing 100% O2 has serious hypoxemia.

Airway mechanics: Pressure volume curves, compliance and resistance

Pressure and its relationship to volume are very important in lung physiology. Below is a pressure-volume curve (loop) of a normal lung. The slope of the line (represented by the solid line) is the change in unit volume per change in unit pressure and is termed "compliance." Note that even at zero pressure there is still some residual volume in the lung (FRC).

The dashed line represents the compliance of the lung. A low compliance means the lung does not expand well at increasing pressures. It is a "stiff" lung. Reduced compliance can be seen in diseases causing alveolar flooding (harder to expand lung), atelectasis (hard to inflate alveoli), and fibrotic states. Loss of alveolar surfactant can also contribute to decreased compliance resulting in atelectasis, and alveolar flooding.



The last property to discuss in the lung is resistance. Resistance is the pressure difference between the alveoli and the mouth. Bronchoconstriction will narrow the airways and cause increased resistance to airway flow. Collapsed airways (small and large) will contribute to resistance as well.

Metabolic functions of the lung

The lung is involved in several different aspects of metabolism. First it regulates CO2 in the bloodstream which directly corresponds to acid contribution to the acid-base status of the body. Hypercarbia leads to retained carbonic acid and a respiratory acidosis. In contrast, it can serve as an acid-release conduit in metabolic acidosis situations. If a patient is in a diabetic ketoacidotic crisis, tidal volume or minute volume can increase, leading to CO_2 loss and an increase in blood p_H. The lung is also responsible for the conversion of angiotensin I to angiotension II via angiotensin-converting enzyme (ACE). The reaction takes place in the lungs and the release of angiotensin II leads to systemic vascoconstriction and heart remodeling in cardiac disease. In addition, the inflammatory mediators of the arachidonic acid cascade (leading to leukotriene and prostaglandin formation) are metabolized in the lung and then distributed into the systemic circulation.

Conclusion

The respiratory system is much more complicated than we once thought. As technicians we need to have a thorough understanding of respiratory physiology to better serve our patients, whether they are in respiratory distress, or simply receiving sedation.

References available upon request